1. Overview

1.1 Introduction

The human exploration of Mars will be a complex undertaking. It is an enterprise that will confirm the potential for humans to leave our home planet and make our way outward into the cosmos. Though just a small step on a cosmic scale, it will be a significant one for humans, because it will require leaving Earth with very limited return capability. The commitment to launch is a commitment to several years away from Earth, and there is a very narrow window within which return is possible. This is the most radical difference between Mars exploration and previous lunar explorations.

Personnel representing several NASA field centers have formulated a "Reference Mission" addressing human exploration of Mars. This report summarizes their work and describes a plan for the first human missions to Mars, using approaches that are technically feasible, have reasonable risks, and have relatively low costs. The architecture for the Mars Reference Mission builds on previous work, principally on the work of the Synthesis Group (1991) and Zubrin's (1991) concepts for the use of propellants derived from the martian atmosphere. In defining the Reference Mission, choices have been made. In this report, the rationale for each choice is documented; however, unanticipated technology advances or political decisions might change the choices in the future.

One principal use of the Reference Mission is to lay the basis for comparing different approaches and criteria in order to select better ones. Even though the Reference Mission appears to have better technical feasibility, less risk, and lower cost than previous approaches, improvement is still needed in these areas to make the first piloted Mars mission a feasible undertaking for the spacefaring nations of Earth. The Reference Mission is not implementable in its present form. It involves assumptions and projections, and it cannot be accomplished without further research, development, and technology demonstrations. It is also not developed in the detail necessary for implementation, which would require a systematic development of requirements through the system engineering process. With this in mind, the Reference Mission may be used to:

- Derive technology research and development plans.

- Define and prioritize requirements for precursor robotic missions.
- Define and prioritize flight experiments for precursor human missions, such as those involving the Space Shuttle, Mir, or the International Space Station.
- Understand requirements for human exploration of Mars in the context of other space missions and research and development programs, as they are defined.
- Open discussion with international partners in a manner that allows identification of potential interests of the participants in specialized aspects of the missions.
- Provide educational materials at all levels that can be used to explain various aspects of human interplanetary exploration.
- Describe to the public, media, and political system the feasible, long-term visions for space exploration.
- Establish an end-to-end mission baseline against which other proposals can be compared.

However, the primary purpose of the Reference Mission is to stimulate further thought and development of alternative approaches which can improve effectiveness, reduce risks, and reduce cost. Improvements can be made at several levels; for example, in the **architectural**, **mission**, and **system** levels.

- The **architectural** level involves assembly of all elements into an integrated whole. The principal features to be addressed in a new architecture that will improve on the Reference Mission appear to be simplification (particularly the number of separate elements that must be developed) and integration with other programs. Simplification by reduction of system elements can lower life-cycle costs and diminish both programmatic and technical risk. For example, the development of higher performance space propulsion systems can lead to simplification, particularly if one vehicle can be used for transit to and from Mars. Integration opportunities to link the Mars program with other development programs could reduce total cost through sharing of developmental costs. The Reference Mission did not assume integration with a lunar exploration program. The development of a major Earth-orbiting operations center in another program could lead to major changes in the Reference Mission architectural approach.
- At the **mission** level, it may be possible to reduce the number of separate launches from Earth. Reducing the total number of launches required to implement the Reference Mission objectives could potentially reduce program and technical risk as well as cost. Focusing and streamlining mission

objectives and improving technology that will lower mass and power requirements can improve the mission level.

- At the **system** level, the performance of individual systems and subsystems can be improved through research and development programs. The programmatic and technical risks can be reduced by demonstrations of ground, Earth-orbit, or planet surface (including the Moon) technology. Criteria for improved systems are principally technical—reduced mass, reduced power, increased reliability.

The current section of this report provides a brief overview of the origins of the study and the Reference Mission design, specifically discussing key issues, findings, and recommendations. Section 2 of this report addresses what can be learned by undertaking the Reference Mission and describes the scientific and technical objectives of Mars exploration. Section 3 provides a detailed discussion of the mission life cycle, the systems needed to carry it out, and the management challenges and opportunities that are inherent in a program to explore Mars with humans.

1.2 Background

The Mars Exploration Study Project was undertaken to establish a vision for the human exploration of Mars that would serve as a mechanism for understanding the programmatic and technical requirements that would be placed on existing and planned Agency programs.

In August 1992, the first workshop of the Mars Study Team held at the Lunar and Planetary Institute in Houston, Texas, addressed the “whys” of Mars exploration to provide the top-level requirements from which the Mars exploration program could be built (Duke and Budden 1992). The workshop attendees identified the major elements of a potential rationale for a Mars exploration program as:

- Human Evolution – Mars is the most accessible planet beyond the Earth-Moon system where sustained human presence is believed to be possible. The technical objectives of Mars exploration should be to understand what would be required to sustain a permanent human presence beyond Earth.
- Comparative Planetology – The scientific objectives of Mars exploration should be to understand the planet and its history, and therefore to better understand Earth.
- International Cooperation – The political environment at the end of the Cold War may be conducive to a concerted international effort that is appropriate to, and may be required for, a sustained Mars program.
- Technology Advancement – The human exploration of Mars currently lies at the ragged edge of achievability. The

necessary technical capabilities are either just available or on the horizon. Commitment to the program will both effectively exploit previous investments and contribute to advances in technology.

- Inspiration – The goals of Mars exploration are grand; they will motivate our youth, benefit technical education goals, and excite the people and nations of the world.

The study team of personnel from NASA field centers used these inputs to construct the Reference Mission, and then translated the inputs into a set of goals and objectives. Ground rules and assumptions were agreed upon and reflect the lessons learned from previous study efforts. From this work, a mission and a set of systems were developed.

1.3 Reference Mission Summary

1.3.1 Objectives

Reflecting the conclusions of the August 1992 workshop, three objectives were adopted for the analysis of a Mars exploration program and the first piloted missions in that program. They are to conduct:

- Human missions to Mars and verify a way that people can ultimately inhabit Mars.
- Applied science research to use Mars resources to augment life-sustaining systems.
- Basic science research to gain new knowledge about the solar system's origin and history.

The human missions to Mars, which are required to accomplish the exploration and research activities, also contain requirements for safe transportation, maintenance on the surface of Mars, and return of a healthy crew to Earth. The surface exploration mission envisions approximately equal priority for applied science research (that is, learning about the environment, resources, and operational constraints that would allow humans eventually to inhabit the planet) and basic science research (that is, exploring the planet for insights into the nature of planets, the nature of Mars' atmosphere and its evolution, and the possible past existence of life). These more detailed objectives form the basis for defining the required elements and operations for the Reference Mission.

In addition, past mission studies have yielded results that have characterized piloted Mars missions as being inherently difficult and exorbitantly expensive. To confront these commonly accepted beliefs that are unfortunately tied to Mars missions, this study added objectives to:

- Challenge the notion that the human exploration of Mars is a 30-year program that will cost hundreds of billions of dollars. Although the nations of the world could afford such expenditures in comparison to, for example, military budgets, the smaller the total cost, the more likely it is that the program will be implemented.

- Challenge the traditional technical obstacles associated with sending humans to Mars.
- Identify relevant technology development and investment opportunities that benefit both Mars exploration and Earth-bound endeavors.

From these basic objectives, a Reference Mission was crafted by drawing on lessons learned from many past studies and by adding new insights to various aspects of the mission. This approach substantially improved the yield from piloted missions while also reducing risk and cost.

1.3.2 Ground Rules and Assumptions

Translating these objectives into specific missions and systems for the Reference Mission required adopting a number of ground rules and assumptions. These were to:

- Balance technical, programmatic, mission, and safety risks.
- Provide an operationally simple mission approach emphasizing the judicious use of common systems.
- Provide a flexible implementation strategy.
- Limit the length of time that the crew is continuously exposed to the interplanetary space environment.
- Define a robust planetary surface exploration capacity capable of safely and productively supporting crews on the surface of Mars for 500 to 600 days each mission.
- Define a capability to be able to live off the land.
- Rely on advances in automation to perform a significant amount of the routine activities throughout the mission.
- Ensure that management techniques are available and can be designed into a program implementation that can substantially reduce costs.
- Use the Earth-Mars launch opportunities occurring from 2007 through 2014. A 2009 launch represents the most difficult opportunity in the 15-year Earth-Mars cycle. By designing the space transportation systems for this opportunity, particularly those systems associated with human flights, they can be flown in any opportunity with either faster transit times for the crew or increased payload delivery capacity.
- Examine three human missions to Mars. The initial investment to send a human crew to Mars is sufficient to warrant more than one or two missions. Each mission will return to the site of the initial mission thus permitting an evolutionary establishment of capabilities on the Mars surface.

Although it is arguable that scientific data return could be enhanced by a strategy where each human mission went to a different surface site, the goal of understanding how humans can inhabit Mars seems more logically directed toward a single outpost approach.

1.3.3 Mission and Systems

Previous studies of human exploration of Mars have tended to focus on spacecraft and flight, rather than on what the crew would do on the surface. The Reference Mission takes the point of view that surface exploration is the key to the mission, both for science and for evaluation of the potential for settlement. As a consequence, the Reference Mission architecture allows for a robust surface capability with significant performance margins: Crews will explore in the vicinity of the outpost out to a few hundred kilometers, will be able to study materials in situ and in a surface laboratory, and will be allowed to update and modify the exploration plan to take advantage of their discoveries.

In addition, key technologies will be developed and demonstrated to test settlement issues, potentially imposing a substantial workload on the Mars exploration crew. To improve the effectiveness of surface operations, supporting systems must be highly reliable, highly autonomous, and highly responsive to the needs of the crew. Some needs may not be anticipated during crew preparation and training, which will significantly challenge the management and operations systems to support the crew in the new situations.

1.3.3.1 Mission Design

The crew will travel to and from Mars on relatively fast transits (4 to 6 months) and will spend long periods of time (18 to 20 months; 600 days nominal) on the surface, rather than alternative approaches which require longer times in space and reduce time on the surface. Figure 1-1 illustrates a typical trajectory. Designed to the worst-case mission opportunity (2007-2009) of the next two decades, the transit legs are less than 180 days in both directions. For easier Mars mission opportunities (for example, 2016-2018), the transit legs are on the order of 130 days. Shorter transit times reduce the time spent by the crew in zero g to the length of typical tours of duty for the International Space Station. (Thus, the Mars Study Team chose not to use artificial gravity spacecraft designs for the Reference Mission.) In addition, relatively fast transits will reduce the exposure to galactic cosmic radiation and the probability of encountering solar particle events. Reducing the exposure to zero g and radiation events helps reduce the risk to the crew.

The strategy chosen for the Reference Mission, generally known as a “split mission” strategy, breaks mission elements into pieces that can be launched directly from Earth with launch vehicles of the Saturn V or Energia class, without rendezvous or assembly in low

Earth orbit (LEO). The strategy has these pieces rendezvous on the surface of Mars, which will require both accurate landing and mobility of major elements on the surface to allow them to be connected or to be moved into close proximity. Another attribute of the split mission strategy is that it allows cargo to be sent to Mars without a crew during the same launch opportunity or even one or more opportunities prior to crew departure. This allows cargo to be transferred on low energy, longer transit time trajectories and the crew to be sent on a required higher energy, shorter transit time trajectory. Breaking the mission into two launch windows allows much of the infrastructure to be emplaced and checked out before committing a crew to the mission, and also allows for a robust capability, with duplicate launches on subsequent missions providing either backup for the earlier launches or growth of initial capability.

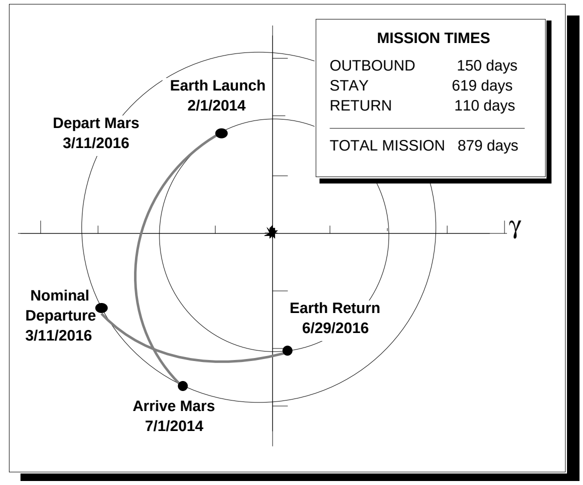

Figure 1-1 Typical fast-transit trajectory.

Figure 1-2 illustrates the mission sequence analyzed for the Reference Mission. In this sequence, three vehicles will be launched from Earth to Mars in each of four launch opportunities which, for reasons presented earlier, start in 2007. The first three launches will not involve a crew but will send infrastructure elements to low Mars orbit and to the surface for later use. Each of the remaining opportunities analyzed for the Reference Mission will send one crew and two cargo missions to Mars. These cargo missions will consist of an Earth-return vehicle (ERV) on one flight and a lander carrying a Mars-ascent vehicle (MAV) and additional supplies on the second. This sequence gradually builds up assets on the martian surface so that at the end of the third crew's tour of duty, the basic infrastructure could be in place to support a permanent presence on Mars.

The six launches used to support the activities of the first crew will be discussed in more detail here to illustrate what will typically occur for all three crews. (Note: For the nominal mission, launches 1 through 4 are required to support the first crew; launches 5 and 6 provide backup systems for the first crew and, if not used, are available for the second crew.) Figure 1-3 illustrates the general sequence of events associated with the first crew's mission to Mars as discussed in the following paragraphs.

In the first launch opportunity, three cargo missions are sent on minimum energy trajectories direct to Mars (that is, without assembly or fueling in LEO). Launch 1 delivers a fully fueled ERV to Mars orbit. (The crew will rendezvous with this stage and use it to return to Earth after completion of their surface exploration mission.) Launch 2 delivers an unfueled MAV, a propellant production module, a nuclear power plant, liquid hydrogen (to be used as a reactant to produce the ascent vehicle propellant), and approximately 40 tonnes of additional payload to the surface. After the descent stage lands on the surface, the nuclear reactor autonomously deploys itself several hundred meters from the ascent vehicle. Using the Mars atmosphere as feedstock, the propellant production module begins to manufacture the nearly 30 tonnes of oxygen and methane that

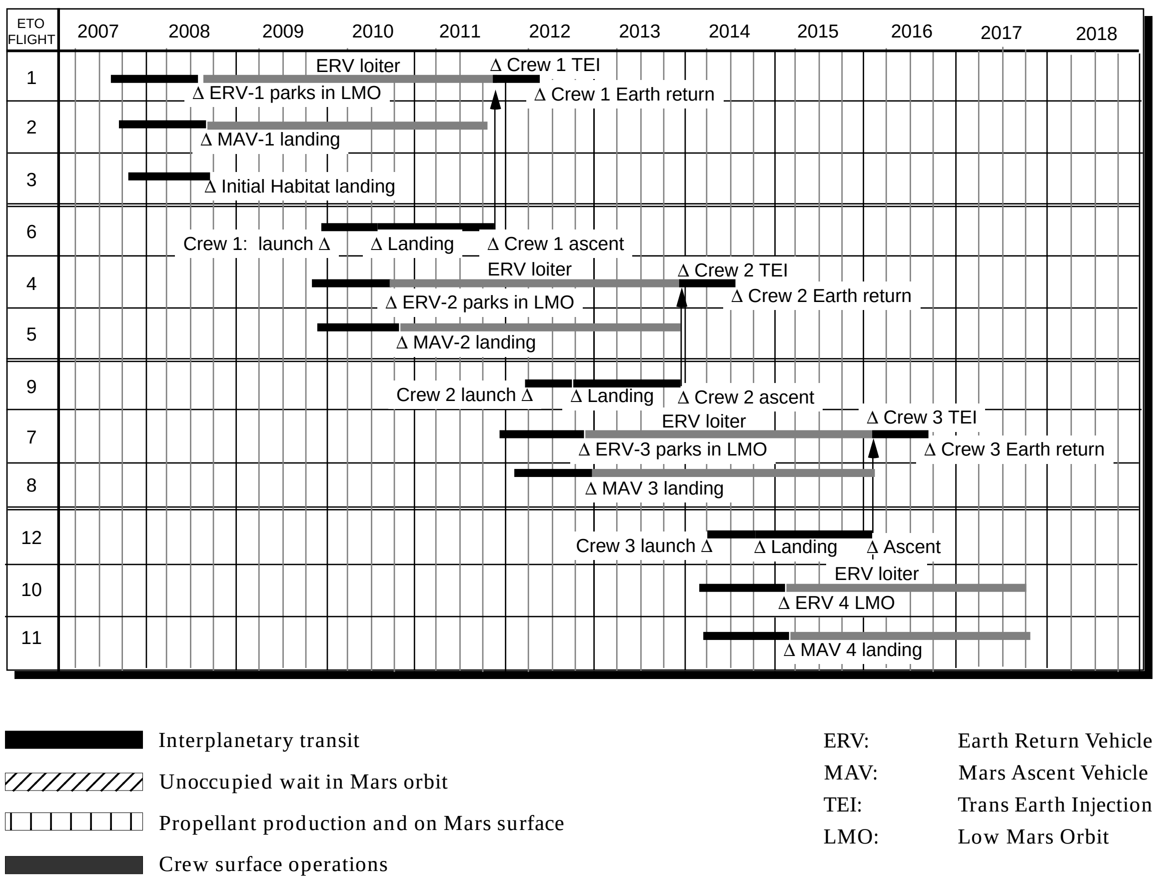

Figure 1-2 Mars Reference Mission sequence.

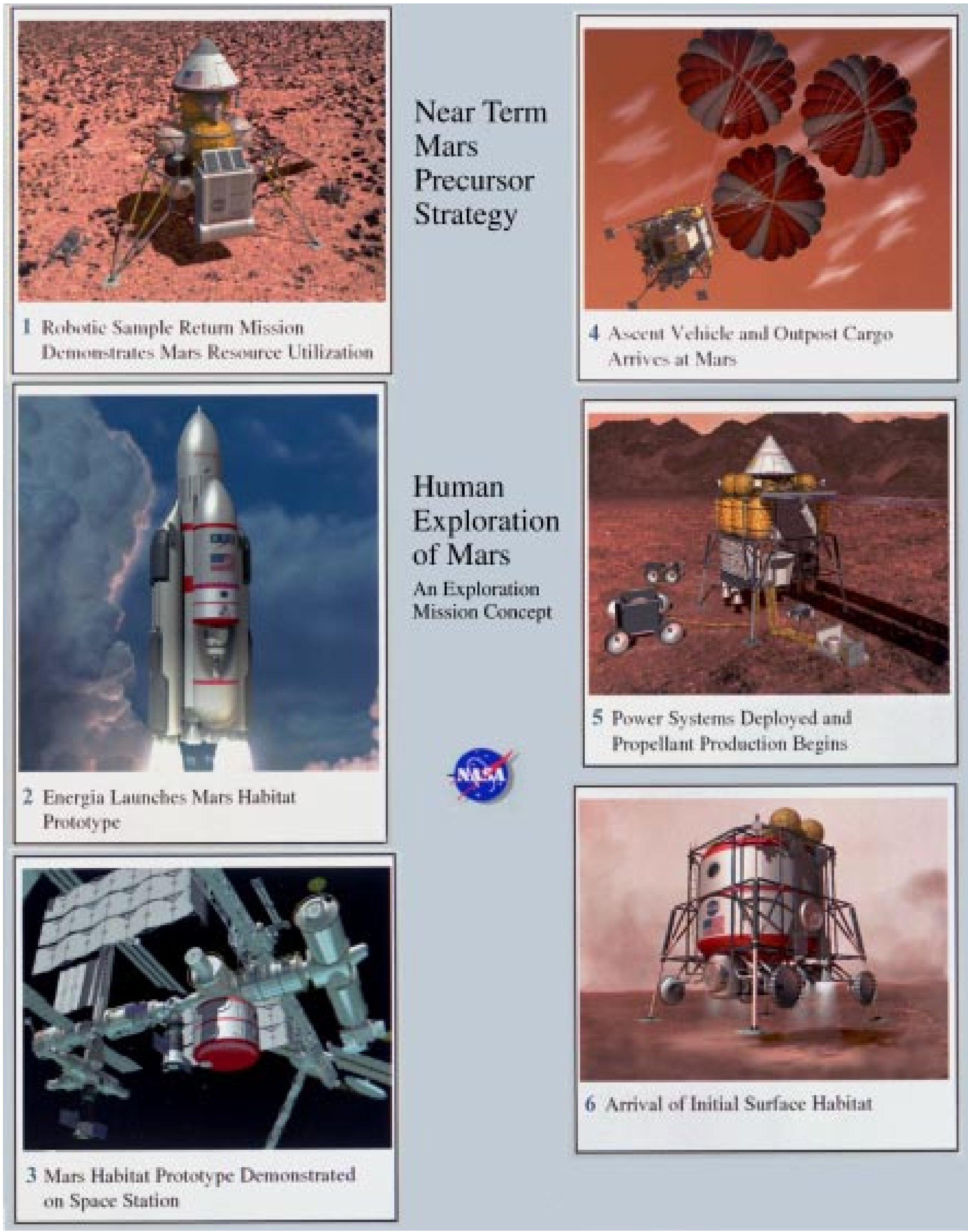

Figure 1-3 General sequence of events associated with first mission to Mars.

Figure 1-3 General sequence of events continued.

will be required to eventually deliver the crew to Mars orbit. This production is completed within approximately one year—several months prior to the first crew's scheduled departure from Earth. Launch 3 lands in the vicinity of the first descent vehicle and delivers a surface habitat/laboratory, nonperishable consumables for a safe-haven, and a second nuclear power plant to the planetary surface. The second nuclear power plant autonomously deploys itself near the first power plant. Each power plant can provide sufficient power (160 kWe) for the entire mature surface outpost, thereby providing complete redundancy within the power production function.

During the second launch opportunity, two additional cargo missions and the first crew are launched. All assets previously delivered to Mars have been checked out and the MAV, already on the martian surface, is verified to be fully fueled before either the crew or the additional cargo missions are launched from Earth. (Should any element of the surface system required for crew safety or critical for mission success not check out adequately, the surface systems will be placed in standby mode and the crew mission delayed until the systems can be replaced or their functions restored. Some systems can be replaced using hardware originally intended for subsequent missions; others may be functionally replaced by other systems.) The first cargo launch of this second opportunity is a duplicate of Launch 1 from the first opportunity, delivering a second fully fueled ERV to Mars orbit. The second cargo launch similarly mirrors Launch 2 of the previous opportunity, delivering a second unfueled ascent vehicle and propellant production module. These systems provide backup or extensions of the previously deployed capabilities. For example, the second MAV and second ERV provide the first crew with two redundant means for each leg of the return trip. If, for some reason, either the first ascent vehicle or the first return vehicle becomes inoperable after the first crew departs Earth, this crew can use either of the systems launched in the second opportunity instead. If the first ascent and return vehicles operate as expected, then the systems delivered in the second opportunity will support the second crew that will launch to Mars in the third opportunity.

The first crew of six departs for Mars in the second opportunity. They leave Earth after the two cargo missions have been launched, but because they are sent on a fast transfer trajectory of only 180 days, they will arrive in Mars orbit approximately 2 months before the cargo missions. The crew lands on Mars in a surface habitat substantially identical to the habitat/laboratory previously deployed on the martian surface. After capturing into a highly elliptic Mars orbit, the crew descends in the transit habitat to rendezvous on the surface with the other elements of the surface outpost. (The crew carries sufficient provisions for the entire surface stay in the unlikely event that they are unable to rendezvous on the surface with the assets previously deployed.)

Surface exploration by robotic vehicles and human explorers will include a wide range of activities.

- Observing and analyzing the surface and subsurface geology.
- Observing and analyzing the composition and structure of the atmosphere.
- Collecting samples and examining them in the outpost laboratory.
- Performing experiments designed to gauge the ability of humans to inhabit Mars.

Prior to the arrival of the first human crew, telerobotic rovers (TROVs) may be delivered to the surface. (These rovers are assumed to be intelligent enough to perform broadly stated objectives without human assistance. But humans will continue to monitor progress and be available to “supervise” the TROV if it cannot solve a particular problem.) When the crew arrives, the rovers will be available for teleoperation by the crew. The TROVs may be designed to provide global access and may be able to return samples to the outpost from hundreds of kilometers distance from the site if they are deployed 2 years before the crew arrives.

The outpost laboratory will be outfitted to provide mineralogical and chemical analyses of rocks, soils, and atmospheric samples; and depending on technical development, it may be possible to undertake simple kinds of geochronologic analysis on Mars. The purpose of these studies would be to support the field investigations, answer “sharper” questions, and allow the human explorers to narrow their focus to the sites of optimum sample collection. As hypotheses evolve, crews will be able to return to sample sites and gather specific samples to test the hypotheses. Ultimately, selected samples will be returned to Earth for more detailed analysis.

As experience grows, the range of human exploration will grow from the local to the regional. Regional expeditions, lasting perhaps 2 weeks and using mobile facilities, may be conducted at intervals of a few months. Between these explorations, analysis in the laboratory will continue. The crew will also spend a significant portion of its time performing maintenance and housekeeping tasks (system design requirements addressing enhanced reliability and maintainability will help keep these activities to a minimum). Figure 1-4 provides a possible time line for the first surface mission.

The deployment of a bioregenerative life support capability will be an early activity after crew landing. Although this system is not required to maintain the health and vitality of the crew, it will improve the robustness of the life support system and is important to the early objectives of the outpost.

Crew activities related to living on another planet should be viewed as experiments. With minor modifications in

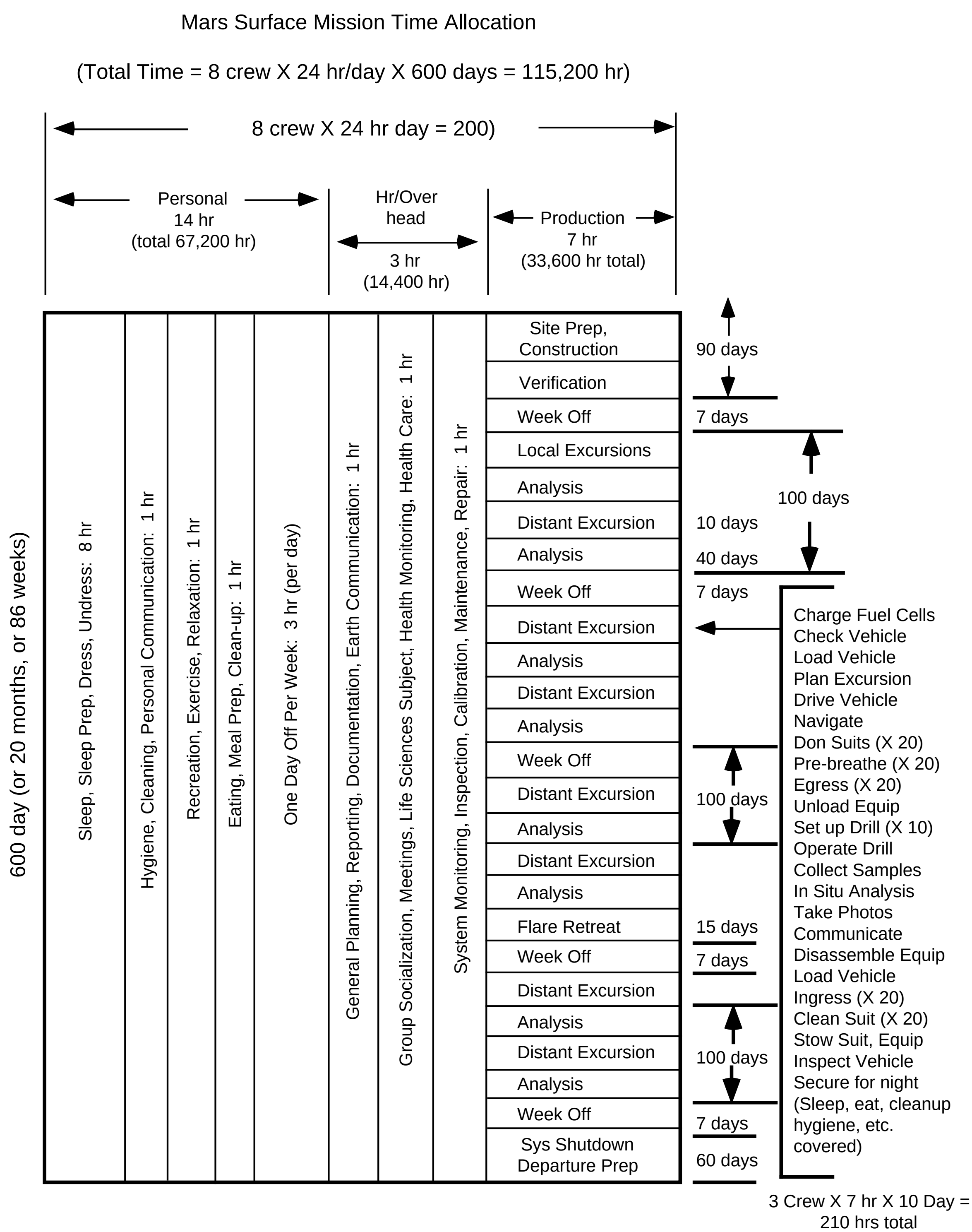

Figure 1-4 Possible time line for first Mars surface mission.

hardware and software, ordinary experiences can be used to provide objective databases for understanding the requirements for human settlement.

The first crew will stay at the outpost for 18 to 20 months. Part of their duties will be to prepare the outpost site for the receipt of additional elements launched on subsequent mission opportunities. Since the first crew will have to depart before the second crew arrives, some systems will have to be placed in standby mode.

After their stay on Mars, each crew will use the previously landed and in situ-resource-utilization fueled ascent vehicle to return to orbit where they will rendezvous with the waiting ERV. The crew will return to Earth in a habitat similar to the one used for the outbound transit leg. This habitat, which is part of the ERV deployed in a previous opportunity by one of the cargo flights, typically will have been in an untended mode for nearly 4 years prior to the crew arrival.

1.3.3.2 In Situ Resource Production

The highly automated production of propellant from martian resources is another defining attribute of the Reference Mission. The technology for producing methane and liquid oxygen from the martian atmosphere and some nominal hydrogen feedstock from Earth is an effective performance enhancement and appears to be technologically feasible within the next few years. The split mission strategy allows the propellant production capability to be emplaced, checked out, and operated to produce the required propellant prior to launching the crew from Earth.

In addition to spacecraft propulsion, the production capability on Mars can provide fuel for surface transportation, reactants for fuel cells, and backup caches of consumables (water, oxygen, nitrogen, and argon) for the life support system.

1.3.3.3 Flight Crew

Humans are the most valuable mission asset for Mars exploration and must not become the weak link. The objective for humans to spend up to 600 days on the martian surface places unprecedented requirements on the people and their supporting systems. Once committed to the mission on launch from LEO, the crew must be prepared to complete the full mission without further resupply from Earth. Unlimited resources cannot be provided within the constraints of budgets and mission performance. Their resources will either be with them or will have already been delivered to or produced on Mars. So trade-offs must be made between cost and comfort, as well as performance and risk. Crew self-sufficiency is required because of the long duration of their mission and the fact that their distance from Earth impedes or makes impossible the traditional level of communications and support by controllers on Earth. The crews will need their own skills and training and specialized support systems to meet the new challenges of the missions.

The nominal crew size for this mission is six. This number is believed to be reasonable from the point of view of past studies and experience and is a starting point for study. Considerable effort will be required to determine absolute requirements for crew size and composition. This determination will have to consider the tasks required of the crew, safety and risk considerations, and the dynamics of an international crew. Crew members should be selected in part based on their ability to relate their experiences back to Earth in an articulate and interesting manner, and they should be given enough free time to appreciate the experience and the opportunity to be the first explorers of another planet. Significant crew training will be required to ensure that the crew remains productive throughout the mission.

1.3.3.4 Robotic Precursors

Robotic precursor missions will play a significant role in three important areas of the Reference Mission. The first area is to gather information about Mars that will be used to determine what specific crew activities will be performed and where they will be performed. The second area is to demonstrate the operation of key techonologies required for the Reference Mission. The third is to land, deploy, operate, and maintain a significant portion of the surface systems prior to the arrival of the crew.

For optimum mission performance, it will be necessary to pick a landing site based primarily on its ability to achieve Reference Mission objectives. The site must be consistent with operational considerations, such as landing and surface operational safety. Detailed maps of candidate landing sites built from data gathered by precursor robotic missions will define the safety and operational hazards of the sites, as well as confirm whether access to scientifically interesting locations is possible by humans or robotic vehicles. Robotic surface missions, including missions to return samples, may be required to confirm remotely sensed data from orbit and to satisfy planetary protection issues. To satisfy the human habitation objectives in particular, it would be highly desirable to locate the outpost site where water can be readily extracted from minerals or from subsurface ice deposits. Such a determination may only be possible from data collected by a robotic surface mission.

To accomplish the Reference Mission, key advances in certain critical technologies will need to occur. The robotic precursor missions offer an opportunity to demonstrate the operation of many of those technologies, such as in situ resource utilization, aerocapture, precision landing, etc. The information and experience gained from the demonstration of these technologies will add immeasurable confidence for their use in the human mission.

The first phase of human exploration is the automated landing of surface infrastructure elements, including a system to produce propellant and life support consumables, the first of two habitats, power systems, and surface transportation elements. All of these systems will be delivered, set up, and checked out using robotic systems operated or supervised from Earth. The propellant required for the MAV will be produced and stored as will oxygen and water caches for the habitat. The overall site will be prepared for receipt of the second habitat.

1.3.3.5 Launch Systems

The scale of the required Earth-to-orbit (ETO) launch capability is determined by the mass of the largest payload intended for the martian surface. The nominal design mass for individual packages to be landed on Mars in the Reference Mission is 50 tonnes for a crew habitat sized for six people that is transferred on a high-energy orbit. This requires the capability for a single launch vehicle to be from about 200 to 225 tonnes to LEO.

Because 200-ton-class launch vehicles raise development cost issues, consideration was given to the option of launching pieces to LEO using smaller vehicles and assembling (attaching) them in space prior to launching them to Mars. This smaller launch vehicle (110 to 120 tonnes) would have the advantage of more modest development costs and is within the capability of the Russian Energia program. However, the smaller launch vehicle introduces several potential difficulties to the Reference Mission scenario. The simplest, most desirable implementation using this smaller launch vehicle is to simply dock the two elements in Earth orbit and immediately depart for Mars. To avoid the boiloff loss of cryogenic propellants in the departure stages, all elements must be launched from Earth in quick succession. This places a strain on a single launch facility and its ground operations crews or requires the close coordination of two or more launch facilities. Assembling the Mars vehicles in orbit and loading them with propellants from an orbiting depot just prior to departure may alleviate the strain on the launch facilities, but the best Earth orbit for a Mars mission is different for each launch opportunity. Therefore, a permanent construction or propellant storage facility in a single Earth orbit is not an optimal solution.

The choice of a launch vehicle remains a significant issue for any Mars mission. For the Reference Mission, however, the larger, 200-ton-class launch vehicle has been assumed without specifying a particular configuration.

1.3.3.6 Interplanetary Transportation System

The interplanetary transportation system consists of a trans-Mars injection (TMI) stage, a biconic aeroshell for Mars orbit capture and Mars entry, a descent stage for surface delivery, an ascent stage for crew return to Mars orbit, an Earth-return stage for departure from the Mars system, and a crew capsule (similar to an Apollo Command Module) for Earth entry and landing. As mentioned earlier, the Reference Mission splits the delivery of elements to Mars into cargo missions and human missions, all of which are targeted to the same locale on the surface and must be landed in close proximity to one another. The transportation strategy adopted in the Reference Mission eliminates the need for assembly or rendezvous of vehicle elements in LEO, but it does require a rendezvous in Mars orbit for the crew leaving Mars. The transportation strategy also emphasizes the use of common elements to avoid excessive development costs and to provide operational simplicity.

The TMI stage (used to propel the spacecraft from LEO onto a trans-Mars trajectory) employs nuclear thermal propulsion. Nuclear thermal propulsion was adopted for the TMI burn because of its performance advantages; its advanced, previously demonstrated state of technology development; its operational flexibility; and its inherent mission enhancements. A single TMI stage was developed for both piloted and cargo missions. The stage is designed for the more energetically demanding 2009 fast transit trajectory and then used in the minimum energy cargo missions to carry the maximum payload possible to Mars. In the human missions, the TMI stage uses four 15,000 lb. thrust NERVA (Nuclear Engine for Rocket Vehicle Application)-derivative reactor (NDR) engines (Isp = 900 seconds) to deliver the crew and the surface habitat / descent stage onto the trans-Mars trajectory (Borowski, et al., 1993). After completion of the two-perigee-burn Earth departure, the TMI stage is inserted into a trajectory that will not reencounter Earth or Mars over the course of one million years. The TMI stage used with the crew incorporates a shadow shield between the NDR engine assembly and the LH_2 tank to protect the crew from radiation that builds up in the engines during the TMI burns. Although it may seem wasteful to discard the nuclear stage after one use, the complexity of Mars orbit insertion and rendezvous operations for the return flight are avoided.

As shown in Figure 1-5, the same TMI stage is used in all cargo missions, which allows the transportation system to deliver approximately 65 tonnes of useful cargo to the surface of Mars or nearly 100 tonnes to Mars orbit (250 × 33,793 km) on a single launch from Earth. The TMI stage for cargo delivery requires the use of only three NDR engines, so one NDR engine and the shadow shield are removed from the TMI stage, which reduces cost and improves performance.

Mars orbit capture and the majority of the Mars descent maneuver is performed using a single biconic aeroshell. The decision to perform the Mars orbit capture maneuver was based on the facts that (1) an aeroshell will be required to perform the Mars descent maneuver no matter what method is used to capture into Mars orbit, (2) the additional demands on a descent aeroshell to meet the Mars capture requirements were determined to be modest, and (3) a single aeroshell eliminated one staging event, and thus one more potential failure mode, prior to landing on the surface.

The crew is transported to Mars in a habitat that is fundamentally identical to the

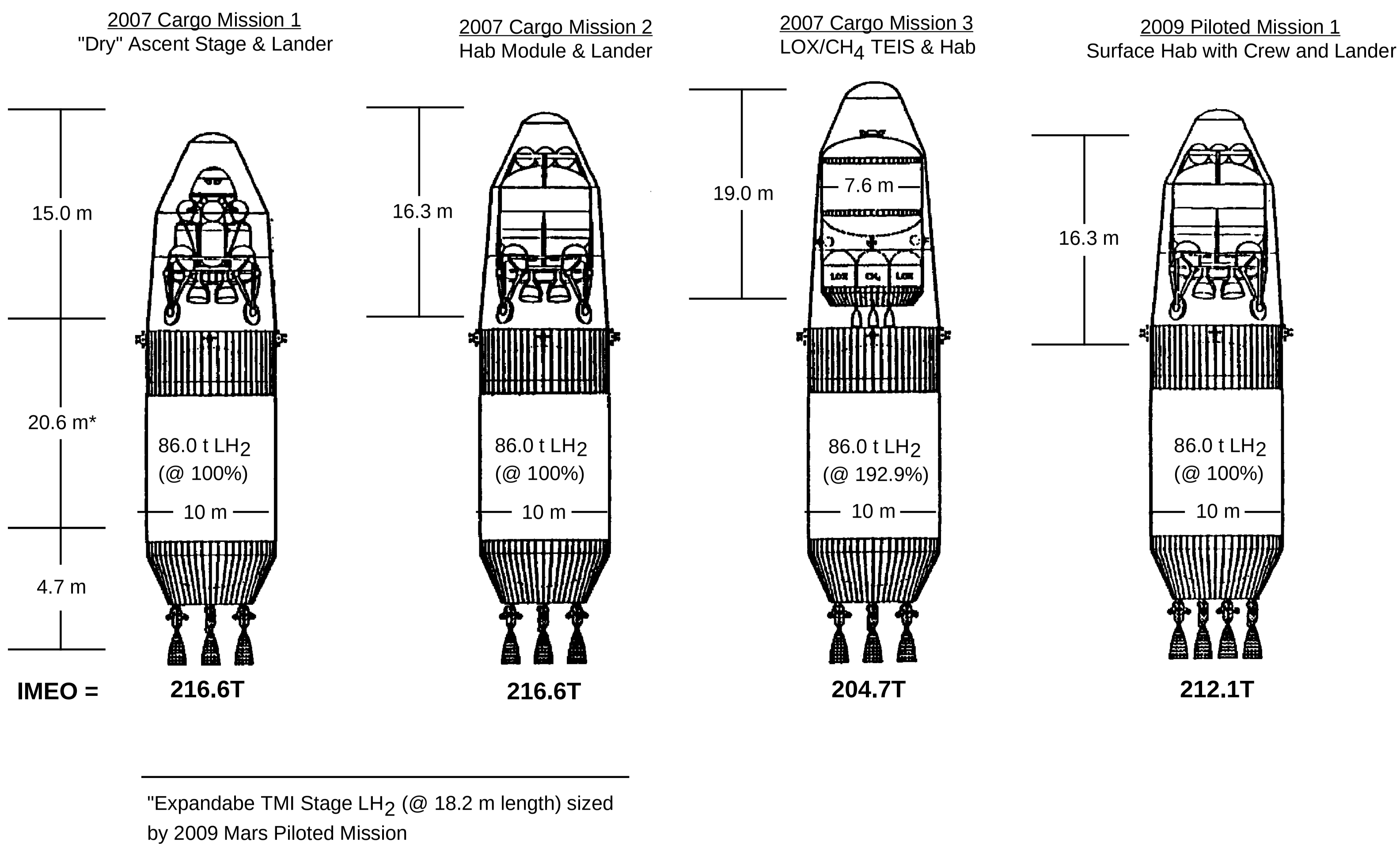

Figure 1-5 Reference Mars cargo and piloted vehicles.

surface habitat deployed robotically on a previous cargo mission. By designing the habitat so that it can be used during transit and on the surface, a number of advantages to the overall mission are obtained.

- Two habitats provide redundancy on the surface during the longest phase of the mission.
- By landing in a fully functional habitat, the crew does not need to transfer from a "space-only" habitat to the surface habitat immediately after landing, which allows the crew to readapt to a gravity environment at their own pace.
- The program is required to develop only one habitat system. The habitat design is based on its requirement for surface utilization. Modifications needed to adapt it to a zero-g environment must be minimized.

A common descent stage has been assumed for the delivery of the transit/surface habitats, the ascent vehicle, and other surface cargo. The descent vehicle is capable of landing approximately 65 tonnes of cargo on the Mars surface. The landing vehicle is somewhat oversized to deliver crew; however, design of a scaled-down lander and the additional associated costs are avoided To perform the postaerocapture circularization burn and the final approximately 500 meters per second of descent prior to landing on the Mars surface, the common descent stage employs four RL10-class engines modified to burn LOX/CH_4. The use of parachutes has been assumed to reduce the descent vehicle's speed after the aeroshell has ceased to be effective and prior to the final propulsive maneuver. The selection of LOX/CH_4 allows a common engine to be developed for use by both the descent stage and the ascent stage, the latter of which is constrained by the propellant that is manufactured on the surface using indigenous materials.

The ascent vehicle is delivered to the Mars surface atop a cargo descent stage. It is composed of an ascent stage and an ascent crew capsule. The ascent stage is delivered to Mars with its propellant tanks empty. However, the descent stage delivering the ascent vehicle includes several tanks of seed hydrogen for use in producing the approximately 30 tonnes of LOX/CH_4 propellant for the nearly 5,600 meters per second delta-V required for ascent to orbit and rendezvous with the ERV. The ascent vehicle uses two RL10-class engines modified to burn LOX/CH_4.

The ERV is composed of the trans-Earth injection (TEI) stage, the Earth-return transit habitat, and a capsule the crew will use to reenter the Earth's atmosphere. The TEI stage is delivered to Mars orbit fully fueled, where it waits for nearly 4 years before the crew uses it to return to Earth. It uses two RL10-class engines modified to burn LOX/CH_4. These are the same engines developed for the ascent and descent stages, thereby reducing engine development costs and improving maintainability. The return habitat is a duplicate of the outbound transit/surface habitat used by the crew to go to Mars, but contains consumables for the return trip only and minimizes crew accommodations required for the surface mission.

1.3.3.7 Surface Systems

The provision of adequate amounts of electrical power is fundamental to a successful exploration program. For the transit phase, the need for power is less severe than on the martian surface. Solar energy is available for crew needs throughout the cruise phase (the transit phase both to and from Mars).

The selection of a power systems strategy for surface operations is guided by risk considerations, which require two-level redundancy for mission-critical functions and three-level redundancy for life-critical functions. The surface power systems should have 15+ year lifetimes to allow them to serve the three mission opportunities with good safety margins. Surface transportation power systems should have 6+ year lifetimes to minimize the need for replacement over the program lifetime.

The strategy adopted for the Reference Mission includes a primary and backup nuclear reactor with dynamic energy conversion. Each system is capable of producing 160 kWe. Additionally, each habitat retains the solar arrays used during transit, and they can also be operated on the martian surface. Due to several factors (for example, the presence of an atmosphere, a day-night cycle, etc.) each power system can produce approximately 30 percent of the power generated in space. For emergency situations, the pressurized rover’s Dynamic Isotope Power System can supply 10 kWe of continuous power.

From a series of volume, mass, and mission analyses, a common habitat structural cylinder, 7.5 meters in diameter, bilevel, and vertically oriented, was derived for the Reference Mission. The three habitation element types identified for the Reference Mission (the surface laboratory, the transit/surface habitation element, and the Earth-return habitation element) will contain substantially identical primary and secondary structures, windows, hatches, docking mechanisms, power distribution systems, life support, environmental control, safety features, stowage, waste management, communications, airlock function, and crew egress routes. The following are brief descriptions of the unique aspects of the three primary habitation elements developed for the Reference Mission analysis.

- The Mars surface laboratory, sent out, landed, and verified prior to the launch of any crew members, will operate only in 3/8 gravity. It contains a large, nonsensitive (that is, no special environmental control required) stowage area with crew support elements on one level and the primary science and research lab on the second level. Future development of this element includes possible retrofitting of the stowage level into a greenhouse as consumables and resources are consumed and free volume is created.

- The Mars transit/surface habitats contain the required consumables for the Mars transit and surface duration of approximately 800 days (180 days in transit and 600 days on the surface) as well as all the required equipment for the crew during the 180-day transfer trip. This is the critical element that must effectively operate in both zero and partial gravity. Once on the surface of Mars, this element will be physically connected with the previously landed surface lab thereby doubling the pressurized volume for the crew. Eventually, all four habitation elements (the surface laboratory and three transit/surface habitats) will be interconnected.
- The Earth-return habitat, functioning only in zero g and requiring the least amount of volume for consumables, will be volume rich but must be mass constrained to meet the limitations of the TEI stage. Since little activity (other than conditioning for the one-g environment on Earth and training for the Earth-return maneuvers) is projected for the crew during this phase of the mission, mass and radiation protection were the key concerns in the internal architecture concepts created.

Extravehicular activity (EVA) tasks consist of maintaining the habitats and surface facilities and conducting a scientific exploration program encompassing geologic field work, sample collection, and deployment, operation, and maintenance of instruments.

Mobility on several scales is required by people operating from the Mars outpost. Crew members outside the habitat will be in pressure suits and will be able to operate at some distance from the habitat, determined by their capability to walk back to the outpost. They may be served by a variety of tools, including rovers, carts, and wagons. On a local scale, perhaps 1 to 10 kilometers from the outpost, exploration will be implemented by unpressurized wheeled vehicles. Beyond the safe range for exploration on foot, exploration will be in pressurized rovers, allowing explorers to operate for the most part in a shirtsleeve environment.

The requirements for long-range surface rovers include having a radius of operation of up to 500 km in exploration sorties that allow 10 workdays to be spent at a particular remote site, and having sufficient speed to ensure that less than half of the excursion time is used for travel. Each day, up to 16 person-hours would be available for EVAs. The rover is assumed to have a nominal crew of two people, but be capable of carrying four in an emergency. Normally, the rover would be operated (maneuvering from site to site, transmitting high data rate communications, supporting EVA activities, etc.) only in the daytime, but could conduct selected investigations at night.

1.3.3.8 Operations

Previous space missions have generally cost more to operate than to design and construct. This phenomenon was caused partly by the fact that systems were designed first and operations were developed to fit the designs. The Reference Mission attempts to bring operational considerations into the process early to better balance the cost of design and development with the cost of operations.

1.3.3.8.1 Crew Operations

The principal difference between Mars exploration and previous space ventures is the requirement for crew operations in an environment where on-call communications, assistance, and advice from ground controllers is not available in emergencies due to the communications delay. This leads to a set of operations requirements that:

- The crew be able to perform autonomously for time-critical portions of the mission.
- Highly reliable, autonomous system operations be possible without intensive crew participation.
- A balance be struck between ground control and the crew on Mars which optimizes the crew’s time and effectiveness yet maintains their independence and motivation to attain mission objectives.

Thus, the Reference Mission will be successful to the degree that ground and flight crews can execute all activities which lead to the accomplishment of mission objectives. All crew activities throughout each mission, from prelaunch through postlanding, constitute crew operations and as such are essential to the overall program. To enhance program success, they must be factored into all aspects of program planning. The majority of crew activities fall into one of four categories: training, science and exploration, systems operations and maintenance, and programmatics.

- Training includes activities such as development of training programs, development of training facilities and hardware, prelaunch survival training for all critical life support systems, operational and maintenance training on mission-critical hardware, prelaunch and in-flight proficiency training for critical mission phases, and science and research training for accomplishing primary science and exploration objectives.
- The majority of science and exploration activities will be accomplished on the surface of Mars and will include, but not be limited to, operating TROVs, habitability exercises, local and regional sorties, and planetary science investigations. Supplemental science objectives may be accomplished during other phases of the mission as well but will be limited by the mass available for onboard science equipment. Those activities required for crew health and safety (such as medical checks during

transit phases, monitoring solar activities for flares, etc.) will be performed.

- During the first mission, a substantial amount of crew time will be devoted to the operation and maintenance of vehicle systems. This time is expected to decrease during subsequent missions as both the systems and operational experience bases mature. However, maximizing the crew’s useful science and exploration time will increase overall mission effectiveness, and the systems or procedures which contribute to increasing this time and decreasing routine operations and maintenance will be incorporated wherever possible.

- Lastly, programmatic activities for flight crews will include public relations, documentation, reporting, and real-time activity planning. Public relations activities have been and always will be an integral part of crew activities. While these activities absorb resources, the most significant of which is time, they also bring public and political support to the program and provide some of the return on investment of the program. Throughout all mission phases, documentation of activities and feedback on training effectiveness will be required of all crews. This will be essential to make effective use of the follow-on crew’s training time and the program’s training hardware and facilities. Many of the mission-critical activities will be planned and rehearsed in great detail before each crew leaves Earth. However, once on the surface of Mars, the very nature of the work done by the crews will require real-time activity planning to take advantage of discoveries made as the mission progresses.

No specific conclusions regarding hardware requirements, facilities requirements, training programs, and the like were derived for this study. But a number of recommendations and guidelines regarding these areas have been developed and tailored to the various mission phases that will be experienced by each crew sent to Mars. While these and other crew activities may not be seen as directly affecting program success, all areas contribute to the successful execution of each mission and, therefore, are essential to the overall success of the Reference Mission.

1.3.3.8.2 Earth-Based Support

The overall goal of Earth-based support operations is to provide a framework for planning, managing, and conducting activities which achieve mission objectives. Achieving this operational goal requires successful accomplishment of the following functions.

- Safe and efficient operation of all resources. This includes, but is not limited to, vehicles, support facilities, training facilities, scientific and systems data, and personnel knowledge and experience bases.

- Provision of the facilities and an environment which allow users (such as scientists, payload specialists, and to an extent crew members) to conduct activities that will enhance the mission objectives.
- Successful management and operation of the overall program and supporting organizations. This requires defining roles and responsibilities and establishing a path of authority. Program and mission goals and objectives must be outlined so that management responsibilities are clear and direct. Confusing or conflicting objectives can result in loss of resources, the most important of which are time and money. In addition, minimizing the number of layers of authority will help to prevent operational decision-making activities from being prolonged.

The Reference Mission, while large and complex, has the added complication of being a program with mission phases which cannot be supported with near real-time operations. Planetary surface operations pose unique operational considerations on the organization of ground support and facilities. A move toward autonomy in vehicle operations, failure recognition and resolution, and mission planning is needed. And ground support must be structured to support these needs.

In general, due to the uniqueness of planetary surface operations, Earth-based support should be assigned the role of managing and monitoring operations planning and execution while crew members will be assigned the actual responsibility for operations planning and execution. Crew members will be told what tasks to do or what objectives to accomplish, but not how to do it. This has the benefit of involving system and payloads experts in the overall planning, yet giving crews the flexibility to execute the tasks. The proposed method for the Reference Mission would take advantage of the unique perspective of crew members in a new environment but would not restrict their activities because of the mission's remote nature. Additionally, it places the responsibility of mission success with the crew, while the overall responsibility for prioritizing activities in support of mission objectives resides with Earth-based support.

After dividing functional responsibilities between Earth-based support and crew, the support may be structured to manage the appropriate functions. To accomplish mission objectives while maintaining the first operational objective of safe and efficient operation of all resources, Earth-based support can be organizationally separated into systems operations and science operations provided a well-defined interface exists between the two. The systems operations team would be responsible for conducting the safe and efficient operation of all resources, while the science operations team would be responsible for conducting activities which support scientific research. Such an organizational structure would dictate two separate operations teams with distinct priorities and responsibilities yet the same operational goal.

Systems operations are those tasks which keep elements of the program in operational condition and support productive utilization of program resources. Thus, the systems operations team has responsibility for conducting the safe and efficient operation of all such resources. The systems operations team consists of representatives from each of the primary systems (power, propulsion, environmental, electrical, etc.) which are used throughout the various mission phases.

The science operations team's sole function is to recommend, organize, and aid in conducting all activities which support scientific research within the guidelines of the mission objectives. The team will consist of representatives from the various science disciplines (biology, medicine, astronomy, geology, atmospherics, etc.) which support the science and mission objectives. Each scientific discipline will have an appropriate support team of personnel from government, industry, and academia who have expertise in that field. The science operations team will act as the decision-making body for all science activities—from determining which activities have highest priority to handling and disseminating scientific data.

Crew and vehicle safety are always of primary concern. When those are ensured, science activities become the highest priority. To accommodate this hierarchy of priorities within the operations management structure, the overall operations manager should reside within systems operations. A science operations manager, who heads the science operations team, should organizationally be in support of the operations manager. Various levels of interfaces between systems engineers and science team members must exist to maximize the amount of science and mission objectives that can be accomplished.

1.3.3.9 Mission and Systems Summary

To summarize, the major distinguishing characteristics of the Reference Mission include:

- No extended LEO operations, assembly, or fueling.
- No rendezvous in Mars orbit prior to landing.
- Short crew transit times to and from Mars (180 days or less) and long surface stay-times (500 to 600 days) for the first and all subsequent crews exploring Mars.
- A heavy lift launch vehicle capable of transporting either crew or cargo direct to Mars, and capable of delivering in four launches all needed payload for the first human mission and in three launches for each subsequent opportunity.
- Exploitation of indigenous resources from the beginning of the program, with important performance benefits and reduction of mission risk.

- Availability of abort-to-Mars surface strategies, based on the robustness of the Mars surface capabilities and the cost of trajectory aborts.
- Common transit / surface habitat design.
- Maintenance of a robust, safe environment for crews throughout their exploration.
- Substantial autonomy of crew and system operations from ground control.

1.4 Testing Principal Assumptions and Choices

A number of assumptions and choices were made in constructing this Reference Mission. For each assumption, this section provides a top-level trade analysis, the rationale for the choice, and guidance to further research and development which could strengthen, improve, or change the choice.

1.4.1 Robust Surface Infrastructure

The principal payoff from Mars exploration lies in surface capability—stay-time, crew safety, exploration range, and other factors that characterize the crew's performance environment. All dictate a robust infrastructure. The choice to land all of the payloads and crews at the same site on four different opportunities was based on the assumption that the marginal cost of additional surface capability would be a cost-effective way to substantially increase the accomplishment of the program.

Two different approaches have been proposed in the past. The first is comparable to the Reference Mission by the long stay-time on the martian surface. The second involves a short stay-time (<30 days on the martian surface) mission. Table 1-1 characterizes principal discriminators of the two scenarios.

In most studies, the short stay-time missions have only been invoked for the first mission; to develop long stay-time capability would require close to total mission redesign and much higher cost for a continued program.

The second alternative is to land each crew at a different location. This scenario would be permitted by the capability defined in the Reference Mission. The principal trade-off is between the additional exploration that might be accomplished by exploring three distant sites versus the benefits of building up the capability to test settlement technologies (such as closed life support systems) and the reduced risk provided by accumulating surface assets at one site. As the range of exploration provided in the single location Mars outpost is high (hundreds of kilometers), the advantages of exploring several landing sites were considered of lower priority for the Reference Mission.

1.4.2 Split Mission Strategy

The split mission strategy takes advantage of the currently available capability to successfully fly and land automated spacecraft on another planet. Such capability can be used to deliver supplies and

Table 1-1 Principal Discriminators of Short and Long Stay-Time Mission Scenarios

	Long Stay-Times	Short Stay-Times	Key Discriminating Factor
Surface Accomplishment	High	Low	Difference in time on surface
Surface risk / day	Low	High	Robust vs. limited surface capability
Surface risk / cumulative	Low	Low	Difference of time vs. robustness
Interplanetary risk	Low	High	
Available to direct launch	Yes	No	
Available to split mission	Yes	Difficult	
Abort to Mars surface	Yes	No	
Availability of Mars at every opportunity	Yes	No	

equipment to support human missions without a crew being present. By using this capability to deliver cargo not absolutely necessary for transporting crews between Earth and Mars, the size of the transportation system (both launch vehicles and upper stages) for any one mission becomes smaller and thus less expensive to develop and manufacture. In addition, these cargo missions can be sent on the absolute minimum energy trajectories between Earth and Mars because there is no time-critical or life support critical element on board. However, the total number of launches increases under this strategy which offsets at least part of the cost savings due to the increased number of transportation elements that must be used.

The split mission strategy is contrasted with the "all-up" approach in which a single vehicle, assembled in LEO, is capable of landing the required assets in a single mission to the surface. The principal trade-off is between rendezvous and assembly in LEO and rendezvous on the Mars surface. For the all-up approach, significant capability is required in LEO to assemble and fuel the spacecraft. Previous designs (the 90-Day Study; see NASA, 1989) projected very high LEO infrastructure costs, which would have to be expended in the early phases of the program. For chemically propelled spacecraft, the logistics of transporting, storing, and loading propellants was excessive and inevitably high in cost. Because the best departure orbit at Earth is different for each Mars opportunity, the space-based infrastructure would have to be moved or reproduced, or additional propulsion penalties be taken to modify the vehicle's departure orbit for every launch to Mars. The elimination of this element in the architecture provides a significant cost reduction. It has been assumed here that the capability of very precise landing on Mars can be developed technically, and that all assets for each flight can be integrated on Earth and simply joined on Mars. These capabilities can be demonstrated on precursor robotic missions.

While the savings resulting from a smaller transportation system may not alone be sufficient to invoke the use of the split mission strategy, the strategy does enhance another assumed element of the Reference Mission—the use of in situ resource utilization. By splitting the missions into cargo and crew flights, infrastructure can be set up and operated before committing a crew to a flight to Mars. Operating this infrastructure for an extended period prior to launching a crew also improves the confidence of using the Mars surface as a safe haven for the crew.

1.4.3 Nuclear Thermal Propulsion

High-performance propulsion is found to be an enabling technology for a human exploration program. Nuclear thermal propulsion was selected because of its higher propellant utilization efficiency and because nuclear rockets were developed almost to flight status in the 1960s. For any given velocity change needed to depart from or be captured at a planet, a nuclear thermal rocket uses approximately 50 percent less propellant than the theoretical best chemical engine. (The Space Shuttle main engine is approaching this theoretical upper limit.) The vast majority of mass needed for a Mars mission is propellant, and any option that reduces the need for propellant can lower the program life cycle cost by reducing the size and number of launch vehicles. Although such rockets might be expensive to test on Earth (the magnitude of which has not been determined) with current environmental concerns, their use in space should not present an environmental issue for they are dangerous only after firing the engines for a significant period of time. Higher performance engines would be better, but typically require a large source of electrical power (from either a nuclear source or very large solar arrays) which calls for additional development to reach the same level of maturity as nuclear thermal rockets.

1.4.4 In Situ Resource Utilization

This technology (assumed to be currently available) has been developed at breadboard level and can be demonstrated on robotic missions. It provides significant benefits to the mission by reducing launch mass from Earth and increasing robustness of surface systems where caches of consumables and surface vehicle fuels can be maintained. As discussed in the previous section, any technology that can reduce the amount of mass (and propellant is the largest single item on such a list) can do much to reduce life cycle cost. This is accomplished primarily by reducing the size and number of launches from Earth and by providing a dual purpose infrastructure that not only provides propellants for a return trip but also supports crew activities and helps reduce risk.

1.4.5 Common Habitat Design

A common habitat was chosen for the Reference Mission primarily to save on cost over the life of the program. Because seven separate habitats will be required to support the three crews sent to Mars, this item becomes a likely candidate for a common approach rather than designing, testing, and building separate systems for the interplanetary leg, the surface leg, and the transition between the two. It may not be feasible to use a common design for all of the components that make up a habitat. However, some of the significant elements—such as the pressure vessel (both primary and secondary structure), electrical distribution, hatches, and docking mechanisms—lend themselves to a common approach. Inasmuch as these major elements of the habitat can be defined and their cost estimated, a common design for the habitats has been adopted for the Reference Mission. A significant amount of work still remains on definition and design of interior details of the habitats which will become part of future efforts associated with Mars mission planning. Study team members were not unanimous in the choice of a common habitat for space transit, for landing on the surface, and for surface habitation. Some argued that, due to the different requirements, a common design was not in the best interest of the mission. This is an area for further research.

1.4.6 Nuclear Surface Power

With no known natural resources on Mars that can be used to generate power, a crew exploring Mars must rely on either converting solar radiation or using a power source they have brought with them. With Mars lying, on average, 50 percent farther from the Sun as Earth, only 44 percent as much solar radiation reaches that planet. This means a crew must bring 2.25 times as much solar energy collecting and converting systems to generate the same amount of power as could be generated on Earth. Add to this a day-night cycle (which requires the addition of an energy charging and storage system) as well as martian dust storms (which significantly diminish the amount of light reaching the surface over extended periods of time) and the size of a solar power station on Mars becomes both large in area and mass and subject to interruption or diminished effectiveness due to the dust storms. Of those sources of energy that can be brought with the crews, only a nuclear power source can concentrate sufficient energy in a reasonable mass and volume. However, other concerns—environmental on Earth, operational on Mars, to name a few—are added to any mission that considers the use of a nuclear power source.

Given these kinds of considerations, a choice was made to rely primarily on nuclear power for systems operating on the martian surface. Power provided by the solar arrays used during the transit to Mars will be available for backup and emergency situations. However, the solar arrays will not be sufficient to power the propellant manufacturing plants that are also a key feature of this mission architecture.

1.4.7 Abort to the Surface

Mars missions differ from Space Shuttle and lunar missions in that once the crew is committed to launch, orbit mechanics force the crew to remain away from Earth for approximately 2 to 3 years. This imposes on all of the systems the need for a higher degree of reliability and maintainability or for multiple independent means of providing life-critical functions (collectively referred to as robustness).

There has been a tendency to view the martian surface as the most hostile location for a crew during a Mars mission. However, of the three environments that a crew will encounter—Earth, interplanetary space, and the martian surface—interplanetary space offers the highest potential for debilitating effects on the crew. Practicality dictates a relatively small habitable space for the crew during transit. To do otherwise causes a corresponding increase in the size and cost of the systems, primarily launch vehicles and transfer stages, associated with the transportation system. But to confine the crew to a small habitable space for an extended duration can lead to cabin fever. Zero g has known debilitating effects on the human body that must be addressed. Radiation from a constant background and the threat of solar flares require that protection be adequate for background sources and that a safe haven be provided for extreme events. All of these threats have engineering solutions that can make the extended stay in interplanetary space a viable prospect for the crew. But the solutions typically require increases in size, mass, and complexity of the vehicle and the transportation elements that are used to move it from planet to planet.

An alternate strategy, and one that was selected for this Reference Mission, is to take advantage of the martian surface as a safe haven where open space, gravity, and radiation protection are naturally available. This strategy, referred to as “abort to the surface,” builds on these naturally available resources and breaks from the previous viewpoint of Mars as the most hostile environment encountered on the mission. The reliability and maintainability of the systems needed to keep the crew alive on the surface is no greater than that imposed on space-based systems. In fact, the buildup of an infrastructure at a single site on the surface enhances the safe haven character of the martian surface. This approach places a greater burden on the entry, landing, and martian-based launch systems. However, the trade-off of making these systems a viable part of the abort strategy through increased redundancy and reliability versus the enhancements needed to sustain a crew through a 2- to 3-year interplanetary abort have tended to favor the abort to the surface strategy. The enhancements that will be made to various systems to allow an abort to the surface also work to the advantage of the overall mission by improving the chances of the crews to successfully reach the surface and perform their exploration activities.

1.4.8 Design for the Most Difficult Opportunity

The design of the Reference Mission was based on the premise that a series of closely spaced missions would result in costs significantly lower than the sum of an equivalent number of single missions. To achieve this cost savings requires that a single set of systems be designed which can accomplish the mission under the most difficult circumstances of any single opportunity. The most significant of these variations results from trajectory differences that occur during sequential mission opportunities. As a result, some systems may have excess capability during some years. However, this allows the advantage of either launching more payload mass in those years with more favorable trajectories or reducing mission durations by flying shorter trajectory legs, but at the expense of greater fuel consumption. For example, in the 2009 opportunity, transit times for piloted missions are approximately 6 months; using the same systems in the 2018 opportunity reduces transit times to just 4 months.

1.5 Conclusions and Recommendations

Based on both mission and programmatic points of view, a number of conclusions and recommendations are made in the following areas: mission and systems, technology development, environmental protection, program cost, international participation, and program management and organization.

1.5.1 Mission and Systems

Conclusions

A feasible mission scenario and suite of vehicles and other systems have been integrated to meet the objectives initially set out for this study. In addition, the Reference Mission addresses a long-standing issue regarding extended-duration flights and crew safety by adopting a view that the surface of Mars is a safe haven and that equipment and procedures should be developed with this in mind.

The Reference Mission includes technology assumptions which require further development and which contribute to an estimated development cost that is higher than can currently be supported. Both technology and cost must be addressed and the alternative missions and systems could result in a better program for human exploration of Mars. However, the mission and systems described here substantially reduce the program cost and at the same time present a more robust approach than in previous studies of this subject.

Recommendations

- Use this study as an informal baseline against which future alternatives should be compared.
- Continue investigating alternative mission scenarios and systems to improve this Reference Mission, or suggest a better alternative.

1.5.2 Technology Development

Conclusions

The Reference Mission was developed assuming advances in certain technology areas thought to be necessary to send people to Mars for a reasonable investment in time and resources. The Reference Mission is not intended to lock in these assumed technologies. The purpose of identifying technologies at this time is to characterize those areas that can either significantly reduce the required mass or cost of the program or significantly reduce its risks (for example, in the area of fire safety). Alternative means of satisfying these requirements may be identified and, if promising, should be supported. The alternatives could be the result of a dual use development, spin off from other programs, or a fortunate “spill over” from some unexpected area.

At this particular stage in developing human exploration missions to Mars, it is difficult to do more than speculate about spin off and spill over technologies that could result from or be useful to this endeavor. However, identifying dual uses for some of the assumed technologies can be started now and, to a certain degree, may be required for such a program to progress. In the current political environment, investment in technology is seen as a means of improving the general quality of life for people on Earth, and multiple use of technologies is emphasized to obtain the best return on the resources invested in their development. The following is a list of twelve technologies which are important to space transportation, humans living in space or on a planetary surface, or the utilization of extraterrestrial resources.

Resource Utilization

- Extraterrestrial mining techniques
- Resource extraction process and chemistry
- Material preparation and handling in reduced gravity
- Extraterrestrial manufacturing

Transportation and Propulsion

- Advanced chemical systems that provide high performance and are compatible with the resources available on the Moon and Mars
- Nuclear propulsion to enable short trip times to Mars
- Aerocapture / aerobraking at the Earth and at Mars for propulsive efficiency and reusable systems
- Lightweight / advanced structures
- Reduced-g combustors

Cryogenic Fluid Management

- Long-term (years) storage in space
- Lightweight and high efficiency cryogenic liquefaction
- Zero g and microgravity acquisition, transfer, and gauging

EVA Systems

- Lightweight, reserviceable, and maintainable suit and PLSS
- Durable, lightweight, high mobility suits and gloves

Regenerative Life Support Systems

- Contamination and particle control
- Loop closure
- Introduction of locally produced consumables
- Food production
- Trash and waste collection and processing
- High efficiency and lighter weight active thermal control systems

Surface Habitation and Construction

- Lightweight structures
- Seal materials and mechanisms
- Construction techniques using local materials

Human Health and Performance

- Zero-g adaptation and countermeasures
- Human factors
- Health care at remote locations
- Radiation protection in transit and on surface

Power Generation and Storage

- Long life, lighter weight, and less costly regenerative fuel cells
- Surface nuclear power of the order of 100kw
- High efficiency solar arrays

Teleoperations / Telerobotics

- Remote operations with long time delays
- Fine control manipulators to support wide range of surface activities
- Telepresence sensors and displays

Planetary Rovers

- Long range (hundreds of km) rovers
- Motor lubricants (long-term use)
- Dust control
- High efficiency lightweight power generation and storage

Advanced Operations

- Automated systems control
- Systems management and scheduling
- Simulations and training at remote locations

Fire Safety

- Fire prevention
- Fire detection
- Fire suppression

Some of these technologies (such as nuclear thermal propulsion, Mars surface space suits, and in situ resource extraction), at the system level, are unique to the Reference Mission or to human space exploration in general. It is likely that NASA or cooperating international partners will have to bear the burden for support of this research and development. The Reference Mission, as it is described here, will fail if these systems are not advanced to a usable state. Other areas, such as medical countermeasures, closed-loop life support systems, autonomous operations systems, surface power systems, and surface mobility, may be of more general interest and may provide opportunities for government and industry to develop shared programs. In still other areas, such as long-lived electronics and materials research, where the underlying research will probably be done by industry to address general problems of technology development, NASA or the international partners should focus on infusing that technology. The exchange of information should be continuous between NASA and the commercial sector particularly concerning the needs of future missions, so that industry can incorporate research into its privately funded programs where it is justified. In all areas, subsystem or component technologies may be developed by industry to meet commercial requirements, and the Mars Program will need to have processes that allow the element designers to use the most advanced capabilities available.

Recommendations

- Establish a Mars Program Office (discussed further under International Participation and Management and Organization) early in the process (now, probably) at a low level to lay the foundation for technology requirements to be undertaken by NASA or other government agencies with similar requirements. Formal organizational agreements should exist between these offices if the technology development is not formally assigned to the Program Office.
- Rank technology investments according to their return to the Program, as either cost or risk reductions.
- Prior to initiation of the Reference Mission, take critical technologies to a demonstration stage. NASA should ensure that experimental work in support of the Reference Mission is incorporated into the International Space Station program at the earliest reasonable time.
- Create a database (in the Program Office) of available technologies that can be used in design studies, and track the progress of these technologies. The database should include domestic and international capabilities.

1.5.3 Environmental Protection

Conclusions

Fundamental principles of planetary environmental protection have been developed since the first planetary exploration missions began in the 1960s. With respect to Mars, the principles adopted by the international scientific community are straightforward: Mars should be protected from biological contamination from Earth that would interfere with or confound the search for natural martian organisms, and Earth must be protected from contamination by martian organisms harmful to the terrestrial biosphere. The United States is signatory to a treaty under the auspices of the Committee on Space Research (COSPAR) which provides the basic framework for its Planetary Protection policy and program (COSPAR 1964 and United Nations 1967).

Planetary protection will be an ongoing discussion at an international level. The policy principles stated here and those that evolve in the future must be carried along as significant requirements for mission planning and system design.

A further political concern is unfortunately tied to the planet Mars. A significant portion of the popular press and the entertainment industry is devoted to speculation about life, intelligent and otherwise, that may exist beyond the planet Earth. Percival Lowell, H. G. Wells, Orsen Wells, and others have placed Mars in the forefront of possible locations for extraterrestrial life. NASA itself has contributed to this perception by supporting legitimate scientific research in this area. Because it is not possible to prove that Mars is completely devoid of life, there is the potential for misinterpretation or misunderstanding when martian materials and human crews are brought back to Earth. For example, an ailment (regardless of the source) among a returning human crew could give rise to speculation that the crew has some unknown Mars “bug” and is about to expose the rest of the human population to its effects.

Recommendations

- Develop adequate and acceptable human quarantine and sample handling protocols early in a Mars exploration program. The protocols must address not only the purely scientific concerns to maintain the pristine nature of samples but also the societal concerns, real or imagined, that are likely to arise.
- Include the protocols as program-level requirements for mission and system development.
- Publicly release for review (by independent authoritative bodies) the principles and practices of contamination control in effect for Mars missions.

1.5.4 *Program Cost*

Conclusions

The cost of the Reference Mission was estimated using standard models. Input for these models was derived from previous experience and information provided by members of the Study Team. Included in the estimate were the development and production costs for all of the systems needed to support three human crews as they explore Mars. In addition, ground rules and assumptions were adopted that incorporated some new management paradigms, as discussed later in the Program Management and Organization section. The management costs captured program level management, integration, and a Level II function. Typical pre-production costs, such as Phase A and B studies, were also included.

Not included in the cost estimate were selected hardware elements, operations, and management reserve. Hardware costs not estimated include science equipment and EVA systems, for which data were not available at the time estimates were prepared; however, these are not expected to add significantly to the total. No robotic precursor missions are included in the cost estimate although their need is acknowledged as part of the overall approach to the Reference Mission. Operations costs have historically been as high as 20 percent of the development cost. However, due to the extended operational period of the Reference Mission and the recognized need for new approaches to managing and running this type of program, estimating the cost for this phase of the program was deferred until an approach is better defined. Similarly, the issue of management reserve was not addressed until a better understanding of the management approach and controls has been developed.

When compared to earlier estimates of a similar scale (NASA, 1989), the cost for the Reference Mission is approximately an order of magnitude lower. A distribution of these costs is shown in Figure 1-6. It can be seen from this figure that the major cost drivers are those associated with the transportation elements: the ETO launch vehicles, the TMI stages, and the Earth-return systems.

The Mars Study Team recognizes that, even with the significant reduction in the program cost achieved by this Team, the Reference Mission is probably still too expensive in today's fiscal environment. More work to further reduce these costs is needed.

Recommendation

- Seek alternative solutions or effective approaches to cost reduction in each of the areas cited above. The efforts may require revolutionary changes throughout NASA, the aerospace industry, the United States, and the world.

1.5.5 International Participation

Conclusions

The human exploration of Mars should be inherently an international, indeed a global, undertaking. Just as the U. S. landing on the Moon excited and amazed the world at U. S. technological skills and organizational accomplishment, the human exploration of Mars can excite and amaze the people of the world with a commonly sought level of technological prowess and organizational capability. The International Academy of Astronautics' International Mars Exploration Study (IAA 1993) describes in more detail the rationale and possible organizational approaches to an international Mars exploration program.

The Reference Mission is rich in possibilities for multinational or even global participation. Many major elements, systems, and subsystems will have to be developed and produced, precursor missions must be developed and flown, and operations capabilities must be developed; and the mission operations can be designed to be undertaken on an international basis. Three types of international participants may

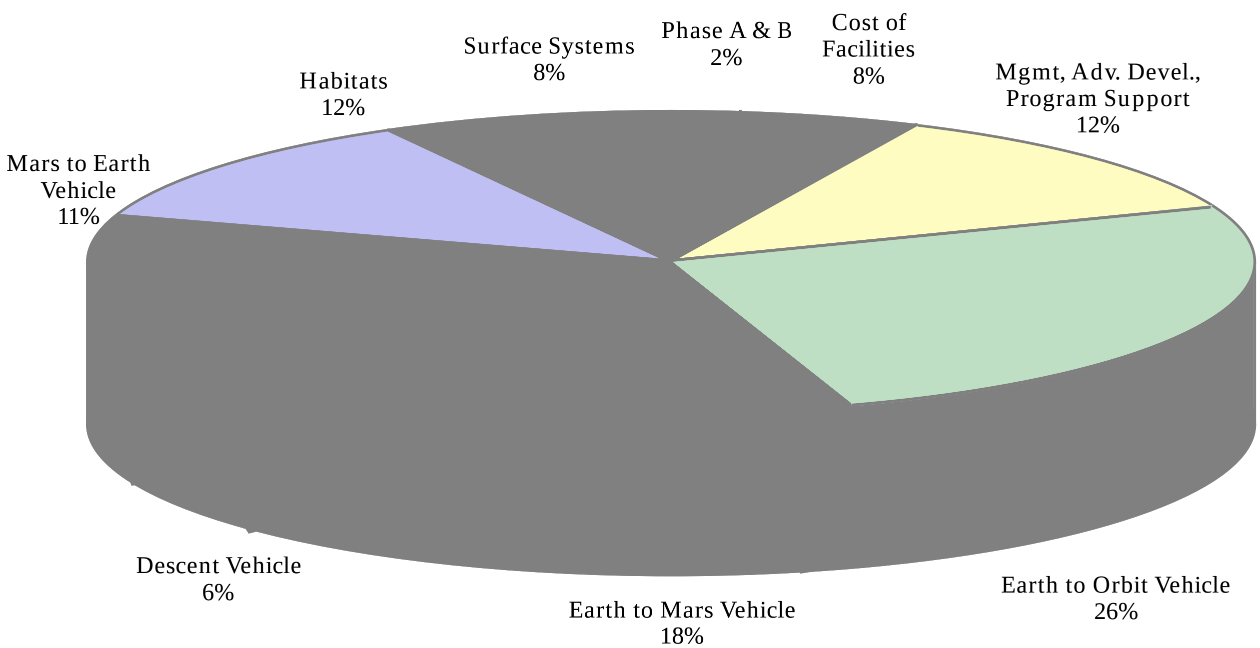

Figure 1-6 Distribution of Reference Mission costs.

contribute based on the ability to provide resources and participate technically in the program.

- Countries with limited resources and technical base. Their participation could be linked to technology transfer to their countries, which could improve the level of technical education and take advantage of technical internship in the endeavor. These relationships might be similar to the participation of Cuba or Viet Nam in the Russian space program.
- Countries with greater amounts of resources and technical base. Their participation would reflect technical interest in limited areas targeted for technical or industrial growth in their economies. The participation of Canada in the International Space Station program is an example.
- Countries with substantial resources and technical base. Their participation would reflect a desire to demonstrate world leadership, retain broad technological skills, and promote aerospace industry. The major contributors to the International Space Station program fall into this category.

All participating countries should expect to gain in proportion to their investment in the enterprise; richer countries might view the program as an opportunity to help poorer countries improve their standards of living through stimulation and transfer of modern technology and technological training.

The ranges of opportunities and interests are large and must be well understood before an international program is constructed. The discussions may be iterative with respect to initial design in order to optimize the collective returns to all nations in the program, and it is not unlikely that 10 years would be needed to formulate the principles and agreements needed to undertake the program. It is important that these discussions lead to a set of basic principles under which the program will be designed and implemented.

Recommendations

- Make the human exploration of Mars program international from its inception, and take as a basic principle that all partners will have a voice in all phases of the program in proportion to the resources contributed to the program.
- Do not exclude any nation even though their participation might be small in economic terms.
- Create a forum in the near future for discussion of the elements of an international program to lay the basis for international participation.
- Create an International Program Office (sensitive to political and technical issues) to lead the design effort. Just as it is important to have all of the design requirements understood prior to development, all of the political requirements must also be understood early in the process.

1.5.6 Program Management and Organization

Conclusions

Organization and management is one of the principal determinants of program cost. This is a rather wide-ranging topic, which is not entirely divisible from the technical content of the program, because it includes program level decision-making that is intimately tied to the system engineering decision-making process. The relationship between program cost and program culture (Figure 1-7) is an indication of that relationship.

The relationship between cost and management style and organizational culture is rather well-known in a general manner, through a large number of “lessons learned” analyses made postprogram. The list of key elements of lower-cost programs (shown in Table 1-2) have been pointed out in a series of analyses, but have not commonly been applied at the critical stage of developing program organization and management approaches. The organizational and management style has been determined rather late in the program, generally because the program content and final design was typically delayed through redesign, changing requirements, and funding irregularities. For example, the International Space Station program went through several redesigns, and some of the hardware was actually in production when the program architecture was modified to integrate the Russian and Space Station Freedom programs. To manage a Mars exploration program to a lowest possible cost, several recommendations are proposed.

Recommendations

- In subsequent studies of the Reference Mission, investigate the design of the organization and management system.
- Reach a formal philosophical and budgetary agreement (between all parties) as to the objectives and requirements imposed on the mission before development is initiated, and agree to fund the project to its completion. In the U. S., this would include multiyear budgetary authority. This should be accompanied by a management process that would protect against program overruns through appropriate incentives.
- Prepare a risk management plan. The human exploration of Mars will have risks that are quite different from any space mission previously undertaken. Two general types of

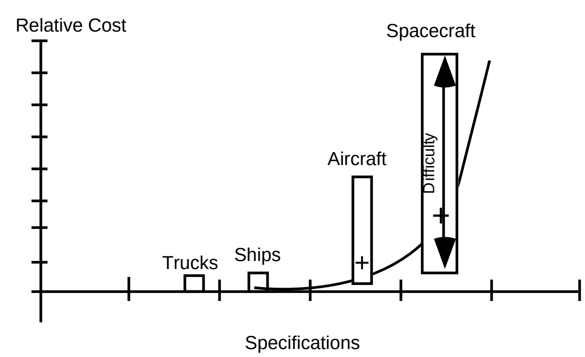

Figure 1-7 Relationship between program cost and program culture.

risk seem to be most critical: risks to the safety of the crew and accomplishment of the mission (primarily technical risks) and risks of not meeting cost and schedule objectives. Maintaining launch schedule is important due to the dependency on several successful launches for mission success and the high cost of missed launch windows. Failure to maintain the launch schedule implies a 2-year program delay at a potentially high program cost.

- Establish a clear demarcation between the design phase and the development and production phase of the project, and do not allow development to begin before the design phase is ended. Prove all technologies prior to initiating production of program elements. Do not change requirements after they are established unless they can be relaxed. Ensure that a system to document the relationship and interaction of all requirements exists and is available for

Table 1-2 Key Elements of Lower-Cost Programs

- Use government only to define requirements.
- Keep requirements fixed: once requirements are stated, only relax them; never add new ones.
- Place product responsibility in a competitive private sector.
- Specify end results (performance) of products, not how to achieve the results.
- Minimize government involvement (small program offices).
- Ensure that all technologies are proven prior to the end of competition.
- Use the private sector reporting system: reduce or eliminate specific government reports.
- Don't start a program until cost estimates and budget availability match.
- Minimize or eliminate government-imposed changes.
- Reduce development time: any program development can be accomplished in 3 to 4 years once uncertainties are resolved.
- Force people off of development programs when development is complete.
- Incentivize the contractor to keep costs low (as opposed to CPAF, CPFF of NASA).
- Use geographic proximity of contractor organizations when possible.
- Use the major prime contractor as the integrating contrator.

use prior to the beginning of production. The Reference Mission requires a number of elements, many of which are technically alike but serve somewhat different functions over the duration of the program. For example, the surface habitat may be the basis for the transit habitat; each of the habitats delivered to the surface will have a different complement of equipment and supplies, according to its position in the delivery sequence. The elements will be developed over a period of several years, and there will be a temptation to improve the equipment and supply manifest. To maintain cost control for the program, requirements must be fixed at the time of initial development.

- Provide clear requirements for the design phase, describing the performance expected and a clear set of criteria for completeness of design as a function of resources expended in design. Use a significant design cost margin to manage the design resources. Terminate the project if a satisfactory design cannot be accomplished within the available resources. Further, select the successful prime contractor as integration contractor for the development phase, and exclude the prime contractor as a development contractor. The design phase of the program is critical to successful cost control, and should be based on a set of functional requirements established by the Program Office (which may well be a multinational activity). The Program Office will be in place to manage technical requirements, provide decisions that require consultation and trade-offs (both technical and political), and manage development contracts. The Program Office should establish functional requirements for the design phase and conduct a competitive procurement for the design phase, with the selection of a prime contractor.

- Prepare a specific construction sequence and plan to accompany each production element of the program. Once committed to development, the development time should be strictly limited if costs are to be contained. This will be difficult in the Mars program, where it probably will be effective to produce common elements sequentially rather than all at one time, although there may be a high enough production rate that costs will drop as experience is gained. A new approach will be needed to ensure that the development time for each individual element is strictly limited.

- Make the two levels of integration, program and launch package, the responsibility of a single organization—a prime contractor to the Program Office. The program will require two levels of integration, similar to that of the International Space Station program: a program level which ensures that overall mission requirements are met at each stage of the mission, that is, for the packages assembled for each launch opportunity; and a launch package level integration, in which all required elements of each launch to Mars are packaged and their performance ensured.

- Include operational considerations in the design and development phases of the program, and use life cycle costs for program design and development decisions. The operational phase of the Mars program must be represented in the design and development phase. This will require a concurrent engineering approach which considers the operational costs as well as the development costs in a life cycle cost approach to the program. If the approaches identified above to separate design and development and to obtain prior commitments for funding for the entire program are successful, there should be less of a problem maintaining the life cycle cost approach to minimizing program costs.
- Put into place positive incentives to maintain program costs within approved levels at all stages of design, development, production, and operations, and to reduce costs of each phase of the program.

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